Phonological Awareness and Short-Term Memory in Hearing and Deaf Individuals of Different Communication Backgrounds

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Previous work in deaf populations on phonological coding and working memory, two skills thought to play an important role in the acquisition of written language skills, have focused primarily on signers or did not clearly identify the subjects' native language and communication mode. In the present study, we examined the effect of sensory experience, early language experience, and communication mode on the phonological awareness skills and serial recall of linguistic items in deaf and hearing individuals of different communicative and linguistic backgrounds: hearing nonsigning controls, hearing users of ASL, deaf users of ASL, deaf oral users of English, and deaf users of cued speech. Since many current measures of phonological awareness skills are inappropriate for deaf populations on account of the verbal demands in the stimuli or response, we devised a nonverbal phonological measure that addresses this limitation. The Phoneme Detection Test revealed that deaf cuers and oral users, but not deaf signers, performed as well as their hearing peers when detecting phonemes not transparent in the orthography. The second focus of the study examined short-term memory skills and found that in response to the traditional digit span as well as an experimental visual version, digit-span performance was similar across the three deaf groups, yet deaf subjects' retrieval was lower than that of hearing subjects. Our results support the claim (Bavelier *et al.*, 2006) that lexical items processed in the visual-spatial modality are not as well retained as information processed in the auditory channel. Together these findings show that the relationship between working memory, phonological coding, and reading may not be as tightly interwoven in deaf students as would have been predicted from work conducted in hearing students.

Key words: **phonological awareness; deaf individuals; ASL**

Introduction

In languages with alphabetic writing systems, individuals typically acquire reading by matching knowledge of the phonological content of their spoken language to the corresponding orthographic representation. This process of applying the alphabetic principle, combined with phonemic awareness and rules of phonics, allows for decoding of words, which eventually leads to reading fluency and comprehension of text (Juel, 1988). Phonological coding or phonological awareness (PA), which is the ability to recognize that words in spoken languages are composed of a set of meaningless discrete segments called phonemes (Scarborough & Brady, 2002) has been shown in hearing children to be a powerful predictor of subsequent reading achievement (Bradley & Bryant, 1985; Adams, 1990; Ehri & Sweet, 1991; Goswami & Bryant,

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1992; Snow, Burns, & Griffin, 1998; Wagner & Torgeson, 1987; Olson, Forsberg, Wise, & Rack, 1994; Torgeson, Wagner, & Rashotte, 1994; Schatschneider *et al*., 2002). In addition, investigations into the relation between early oral language proficiency and later reading outcome have repeatedly shown that comprehension of oral language is a strong predictor of reading ability (Catts *et al*., 2003; Bishop & Adams, 1990; Scarborough, 1989).

In contrast, congenitally deaf children generally do not have sufficient auditory access to spoken languages and for them learning to read is an entirely different endeavor. Many studies have consistently shown that profoundly and prelingually deaf individuals lag significantly behind their hearing peers in standardized measures of reading achievement (Furth, 1966; Karchmer, Milone, & Wolk, 1979; Conrad, 1979; Karchmer & Mitchell, 2003; Traxler, 2000). Their reading abilities vary widely, but national surveys indicate an average of third- or fourth-grade reading level (Furth, 1966; Trybus & Karchmer, 1977; Quigley & Paul, 1986; Allen, 1986; Traxler, 2000). One explanation for this performance deficit is that deafness prevents access to spoken phonology (Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979; Perfetti & Sandak, 2000) and, by extension, the use of phonetic coding in working memory, phonological awareness, and phonetic recoding in lexical access, which are considered to be interdependent hallmarks of successful reading development in hearing children (Wagner & Torgeson, 1987; Tractenberg, 2002). This claim, however, is not without dispute as certain deaf individuals demonstrate evidence of phonological coding (Hanson, 1989; Hanson & Lichtenstein, 1990; Hanson & Fowler, 1987; Leybeart, 1993; Conrad, 1979; LaSasso, Crain, & Leybaert, 2003). Still, others have argued that the reason for limited reading achievement among many deaf students is the lack of higher-order language skills, not phonological decoding, (Chamberlain & Mayberry, 2000), and that levels of comprehension required at the higher grade levels presents an obstacle to reading development. To complicate matters further, there is considerable variability in the use of communication systems among deaf students and their use is usually determined by whether they are born into families of deaf or hearing parents. Unfortunately, many early studies on reading outcomes have not taken into consideration the role of the various communication systems available to the deaf population, each of which may independently influence the degree to which deaf students access written English.

Communication Choices

Generally, deaf and hard-of-hearing individuals living in the United States have three visually based communication choices available to them: (1) sign communication (e.g., American Sign Language); (2) oral/aural communication (the exclusive use of audition, speech/lip-reading, and speech production); and (3) cued speech (CS), which is a communication system designed to visually convey the phonology of spoken languages.

American Sign Language (ASL) is a widely used manual form of communication in the North American deaf community and is recognized by linguists as a fully autonomous natural language, because it contains the same complex linguistic elements as spoken languages: phonology, morphology, syntax, semantics, and prosody (Klima & Bellugi, 1979; Lane & Grosjean, 1980; Wilbur, 1987; Lucas, 1990). In ASL, signs are produced by a combination of parameters (e.g., handshape, place of articulation, movement, and orientation; Stokoe, Casterline, & Croneberg, 1965; Bellugi, Klima, & Siple, 1975). ASL is one of a class of signed languages indigenous to deaf communities around the globe (other languages include British Sign Language and French Sign Language among others) that has evolved independently and are structurally distinct from one another.

Oral/aural communication (sometimes referred to as “lip reading” or “speech reading”) is an approach that places great emphasis and training on the use of speech, residual hearing, and speech reading with the goal of developing intelligible speech, optimal use of residual hearing (generally with the assistance of a hearing aid or cochlear implant), and communicative independence. A national survey reported that 47.8% of more than 37,000 American deaf and hard-of-hearing children use "speech only" as a primary mode of communication (Gallaudet Research Institute, 2005). However, the amount of linguistic information conveyed using the oral method is extremely limited. Research has shown that lip reading single words is only 30% accurate, even in contextual sentences or phrases (Nicholls & Ling, 1982; Clarke & Ling, 1976). Skilled speech-readers often use their grammatical and semantic knowledge to infer messages when the information seen on the lips is ambiguous; this is often referred to in the reading literature as top-down processing (Goodman, 1985).

A much smaller subgroup of deaf individuals uses a communication system commonly known as *cued speech*. This manual system utilizes a set of handshapes to indicate and distinguish (receptively and expressively) the consonants that appear similar on the lips of the "speaker" and a set of hand locations to distinguish vowels that are visibly similar on the mouth of the speaker (Cornett, 1967). For instance, the consonant phonemes /b/, /p/, and /m/ are visually indistinguishable when articulated without the benefit of sound but are fully specified, or differentiated in cued speech via different handshapes for each phoneme. Similarly, the vowel phonemes /I/ and /E/ are easily misperceived in the absence of sound, but are fully distinguished in cued speech via different hand placements. Cued speech is designed to provide the deaf or hard-of-hearing person with clear and unambiguous visual access to the phonemic information of spoken language by combining the different handshapes and locations with natural mouth movements inherent in speech. As a result, deaf children who are exposed to cued speech from an early age have demonstrated comparable phonological knowledge to their hearing counterparts (LaSasso, Crain, & Leybeart, 2003). The national survey reports that 0.3% of more than 37,000 deaf and hard-of-hearing students use cued speech (Gallaudet Research Institute, 2005).

Phonology, Reading, and Deafness

Because of the predictive power of phonological skills in determining reading outcome in hearing students, the role of phonology in deaf students vis-à-vis reading has been a subject of great interest. Historically, the definition of phonemes has often been characterized as sound-based units, in part because much of the literature on phonology has focused on spoken languages (e.g., Wagner & Torgeson, 1987). In reality, phonemes are abstract cognitive units whose physical (or phonetic) forms are typically manifested via speech or cued gestures (Scarborough & Brady, 2002; Hanson, 1989; Fleetwood & Metzger, 1998).

Studies investigating the role of phonology and reading in deaf individuals have focused largely on the recognition or generation of rhymes (as rhyming is seen as an indicator of PA). For example, in a UK-based study of orally raised deaf students, Conrad (1979) found better readers recalled fewer items from rhyming lists of printed letters than from corresponding nonrhyming lists, suggesting that the more proficient deaf readers had access to phonetic coding that interfered with their recall. Campbell and Wright (1988) in a British study of orally raised deaf adolescents and hearing controls found that deaf children performed poorly on a rhyme judgment task as a consequence of being susceptible to orthographic similarity. Moreover, in an effort to match the two groups on reading age (using the Neale reading test), the investigators found that the average chronological age of deaf subjects was almost twice that of their hearing counterparts (14.6 and 7.6, respectively).

In deaf users of sign language, Hanson and Fowler (1987) conducted a series of experiments employing a speeded lexical decision task in which college-aged deaf and hearing participants made decisions as to whether pairs of written items contained words or pseudowords. They found that phonological similarity between word pairs reduced the reading rate of both the hearing and the signing deaf participants, suggesting a similar phonetic coding strategy in the deaf and hearing participants. In another study, Hanson and McGarr (1989) found that signing deaf college students were able to demonstrate a certain level of PA in a rhyme generation task, but not as extensively as those expected of hearing peers, producing only 50% correct responses to written words. Because the participants were considered to be good readers, the authors speculated that PA abilities in these deaf adults may have developed as a consequence of reading experience and that in general, PA skills might not be expected to be present in young, developing readers. It should be noted that these studies by Hanson and colleagues did not identify whether deaf subjects were native users of ASL, making it difficult to infer possible relationships between deafness, signing experience, and PA skills.

In one of the few comparative studies investigating the phonological skills of children from oral, signing, and cueing backgrounds, Charlier and Leybaert (2000) conducted two experiments examining the rhyming abilities of deaf children in Belgium. In the first experiment, children were asked to make rhyme judgments in their native French based on picture stimuli. They found no differences between the hearing group and the group with extensive cued speech exposure (use of cued speech both at home and at school) and both of these groups outperformed all other deaf groups (including those who only used CS at school). In the second experiment, a different group of French deaf cuers and hearing children (mean age = 10.1) were asked to generate rhyming words for pictured and written target items. The results again indicated that the group of children who used cued speech at home and school performed similarly to (although slightly lower than) the hearing control group. More recently, LaSasso and colleagues (LaSasso *et al.*, 2003) used a similar rhyme generation task as Hanson and McGarr (1989) to compare PA performance of college students matched on reading levels (using the Stanford Achievement Test-9, 1996). They compared three groups of skilled readers—hearing, deaf cuers, and deaf noncuers—and found that the deaf cuers had PA skills comparable to their hearing peers and superior to that of the deaf noncuers.

Taken together, these studies generally indicate lower performance on measures of PA in deaf compared to hearing students with evidence of strong PA skills among the more accomplished deaf readers, regardless of communication background. However, there is emerging evidence that the performance gap in measures of reading and PA between hearing and deaf students is considerably less in deaf students who have extensive exposure to cued speech.

Short-Term Memory and Deafness

In addition to PA, phonetic coding of linguistic items (digits, words, etc.) into short-term memory (STM) is also an important predictor of reading development in hearing children (Wagner & Torgeson, 1987). Hearing individuals have been shown to use a phonetic code during short-term recall of linguistic stimuli (Conrad, 1964, 1973, 1977; Healy, 1982); however, the encoding strategy employed by deaf individuals during STM tasks is less clear. An early STM study by Conrad (1970) claimed that deaf subjects, particularly those who are prelingually deaf, do not use this speech-based phonetic coding. However, other studies have noted some evidence of phonetic coding memory in deaf populations during short-term recall of linguistic items (Conrad, 1979; Hanson, 1982; Hanson, 1990), which is thought to be advantageous in their reading achievement (Hanson, Liberman, & Shankweiler, 1984; Lichtenstein, 1985; Lichtenstein, 1998). Specifically, Conrad (1979) tested deaf oral subjects on short-term recall of rhyming printed letters and found decreased performance with rhyming letters compared to unrhymed letters. Hanson (1982) found a similar effect in skilled deaf readers who were native users of ASL when their short-term recall of printed word items decreased with phonetically similar lists, but not orthographically similar lists. Later, Hanson (1990) examined deaf and hearing adults' temporal (and spatial) recall of letters following an articulatory interference task using letter sets that were designed to confuse subjects on the basis of phonetic, manual, and visual similarity. Both deaf and hearing groups were affected by phonetic similarity in the letters and showed no evidence of manual or visual coding during temporal recall.

Whereas the above studies examined the encoding strategies employed by deaf individuals, a number of studies have focused extensively on the amount of linguistic items that subjects recall. While Tractenberg (2002) found comparable digit recall performance between deaf signers and hearing nonsigning subjects, most other studies consistently indicate that deaf individuals recall fewer items than their hearing counterparts (Hanson, 1982; Hanson, 1990; Wallace & Corballis, 1973; Bellugi *et al.*, 1975; Conrad, 1970; Coryell, 2001; Boutla, Supalla, Newport, & Bavelier, 2004; Bavalier, Newport, Hall, Supalla, & Boutla, 2006). Using a computer for stimuli presentation, Coryell (2001) compared the digit span of deaf signers and deaf cuers to age-matched hearing controls and found that deaf signers recalled significantly fewer digit items than did hearing subjects, consistent with previous findings (Conrad, 1970; Wallace & Corballis, 1973; Bellugi *et al.*, 1975). Additional studies have shown that this lower capacity for recall in deaf signers compared to hearing subjects occurs even when rate of articulation and phonological similarity in item presentation is controlled for (Boutla *et al.*, 2004; Bavalier *et al.*, 2006). However, this discrepancy seems to be limited to serial recall, as deaf subjects exhibit recall performance comparable to that of hearing controls during free recall of linguistic items (Hanson, 1982; Boutla *et al.*, 2004).

Deaf cuers, on the other hand, showed comparable performance to hearing controls and significantly greater digit recall than deaf signers (Coryell, 2001). However, it should be noted that this study employed only the forward recall list of the test and that mental reordering skills, such as those required to perform the backward list, was not the focus of the study.

One criticism of these memory capacity studies described above is that differences in linguistic modality and the formational properties between ASL and spoken languages, rather than lack of audition, might account for the differences observed in STM capacities between hearing and deaf participants. More recent studies have addressed this issue with the inclusion of hearing native signers who share the same early ASL experience as deaf signers (Boutla *et al.*, 2004; Wilson & Emmorey, 1998; Bavalier *et al.*, 2006). These studies have found that hearing native signers of ASL recalled fewer items when stimuli were presented in ASL compared to English, suggesting that sign language, and not sensory experience, can negatively affect STM capacity. Considerable debate continues over whether the sequential nature of spoken languages is most advantageous for temporal-order STM tasks compared to the visuospatial nature of signed languages. Wilson and Emmorey (2006a, 2006b) have argued that memory capacity is not affected by language modality but is restricted by processing load and that items taking longer to produce, as in the case of signs, will result in a smaller capacity. In a study carefully controlling for intrinsic factors such as word length, articulation rate, and phonological similarity, hearing nonsigners and deaf signers demonstrated comparable STM span using letter stimuli presented in English and ASL respectively (Wilson & Emmorey, 2006a). In contrast, another study (Bavalier *et al.*, 2006) has asserted that the shorter span for ASL-presented items in deaf and hearing native users of ASL exists independently of such manipulations and is attributed to the differences between the auditory and visual modality during serial memory encoding. Their conclusions arose from their findings that deaf and hearing signers persist in showing decreased digit spans despite efforts to control for rate of stimulus presentation and phonological similarity across languages (Bavalier *et al.*, 2006). Taken together, the STM capacity of deaf individuals has largely been shown to be reduced, but the reason for this difference, whether it is attributed to language modality or cross-linguistic differences, is still poorly understood.

Present Study Questions

In short, the conclusions on the nature of PA and verbal STM in deaf populations remain unsettled. Importantly, these studies have been limited in their inclusion or description of the diverse communication backgrounds available to deaf people, thereby hindering a clear determination of whether any differences observed among hearing and deaf subjects in these two skills can be ascribed to the absence of audition or to their communication modality. While LaSasso and colleagues compared rhyme generation in deaf adult cuers with deaf noncuers (LaSasso *et al.*, 2003), the present study focuses on detection of phonemic units in lexical items and takes a step further by distinguishing deaf noncuers into two groups of oral and signing backgrounds. Likewise, even though the empirical literature is rife with STM studies of deaf oral users and ASL signers (Hanson, 1990; Hanson, 1982; Conrad, 1979; Boutla *et al.*, 2004; Bavalier *et al.*, 2006), the present study includes deaf cuers and extends the findings of Coryell (2001) to include backward digit-span recall (in addition to forward digit span) during verbal presentation of the stimuli in deaf groups of various communication backgrounds. American deaf adults from distinct language/communication backgrounds, ASL, oral English, and cued English were recruited and compared with one another as well as with two groups of hearing subjects, hearing nonsigners, and hearing native signers. In order to specifically address the role of sensory and early language experience on phonemic knowledge and short-term memory, these groups were matched on their reading performance (measured by a test of word recognition) as well as performance IQ. The study of adults, as opposed to children, has the advantage of examining a population whose reading and reading-related skills have reached a mature stage and whose cognitive and linguistic abilities are reflective of lifelong experience with their auditory and communicative systems.

We made several predictions with regards to phonemic knowledge and short-term memory in skilled readers of distinct sensory and language backgrounds. First, because cued speech provides deaf users with unambiguous visual access to English phonology, we predicted that deaf cuers would do well in measures of phonological awareness. By comparison, orally raised deaf adults who without manual cues depend primarily on speech reading to access English and have incomplete visual access to English phonology, and they were predicted to be less proficient in phonemic awareness than cuers. Deaf native users of ASL were predicted to have the least access to English phonology and hence the lowest PA skills of the three deaf groups. Second, we predicted that the examination of STM capacity in the three aforementioned deaf groups compared to hearing subjects would provide valuable insight into potential differences in STM capacity between hearing and deaf proficient readers. Importantly, the present study allows us to examine the interplay of language modality and memory encoding skills. If deaf users of cued speech and oral users, whose visual communication system retains the sequential structure of spoken language, demonstrated comparable performance to that of hearing subjects, then Wilson and Emmorey's (2006a) claim of equal spans across language modalities (while taking language-specific differences into account) would be supported. In other words, as long as the individuals share the same native language (English), STM may be preserved even in the absence of audition. Such a finding could suggest that the lower digit-span scores seen in deaf signers might be attributed to articulatory differences between the two languages and not sensory differences *per* se. If, on the other hand, deaf cuers exhibited lower digit-span capacity than their hearing counterparts, this would support the claim made by Bavalier *et al*. (2006) that linguistic information presented in the visuo-gestural modality is not compatible with the temporal properties of STM in the auditory modality. To address these competing hypotheses, the present study employed two different versions of the digit span, verbal and visual, with the assumption that the visual version of the digit span negates any language-specific differences in stimulus item presentation, such as articulatory rate, duration, and mode of presentation. While it has already been established that digit-span capacity in deaf signers is significantly lower than that of hearing speakers for a number of possible reasons (Hanson, 1982; Wallace & Corballis, 1973; Bellugi *et al*., 1975; Conrad, 1970), concerns about differences in articulatory rate and word length effect across languages (Wilson & Emmorey, 2006a; 2006b) are not at issue here because deaf cuers and oral users share English with hearing speakers as their native language.

Methods

Participants

A total of 51 subjects from five different categories of language and sensory backgrounds were recruited from the metropolitan Washington, DC area: deaf native users of American Sign Language (DA) ($n = 14$); deaf users of cued cpeech (DC) ($n = 9$); deaf oral users of English (DO) ($n = 8$); hearing native users of American Sign Language (HA) ($n = 10$); and hearing native speakers of English (H) ($n = 10$). Hearing controls were recruited from Georgetown University, and deaf and hearing native signers were recruited via flyers posted at Gallaudet University (all participants were college educated with a minimum of 12 years of education). All deaf subjects were born deaf or became deaf before the age of 2 years, with >85 db hearing loss in the better ear. Subjects reported continuous use of their native languages and communication mode from before the age of 5 years until adolescence or beyond. All subjects were healthy with no reported history of reading, mental, or neurological disorders. All subjects were participants in a larger study involving functional brain imaging, and the tests given to subjects below were part of a larger battery of neuropsychological tests spanning two sessions of 3 hours each. For this analysis, subjects were chosen on the basis of their compatibility with regard to performance IQ and reading accuracy; to attain this goal four subjects with performance IQ standard scores of 127 or more were excluded from the analysis. IRB approval was obtained from Georgetown and Gallaudet Universities.

Neuropsychological and Behavioral Tests

All tests were administered to the subjects in their preferred language/communication mode by a hearing research assistant fluent in spoken English, ASL, and cued English, unless described otherwise.

Intelligence Quotient

Performance IQ (PIQ) was measured using the Wechsler Abbreviated Scale of Intelligence (WASI) test (Wechsler, 1999). This instrument contains four subtests, each measuring different aspects of intelligence and using items of increasing difficulty. The Performance IQ score was derived for each participant from the Block Design and the Matrix Reasoning subtest scores. A verbal IQ score was also obtained in four of the five groups using the WASI but will not be reported for the purpose of the current study as it was not obtained for the deaf ASL group.

Word Identification Fluency

The Test of Silent Word Reading Fluency (TSWRF) (Pro-Ed, Inc.) assesses word-identification fluency "as a valid estimate of general reading ability [which] can be used with confidence to identify poor readers" (Mather, Hammill, Allen, & Roberts, 2004). Subjects were presented with rows of words with no spaces between them and asked to draw lines between the boundaries of as many words as possible within 3 minutes. The TSWRF yielded raw scores for accuracy, which were then converted to standard scores through tables provided in the manual.

Reading Comprehension

The Passage Comprehension subtest of the Woodcock–Johnson III test measures silent reading comprehension without time constraints (Woodcock, McGrew, & Mather, 2001). The present reading achievement level of the subject dictates the starting point of the test and the level of difficulty of the test increases by increasing the level of vocabulary, the passage length, and the syntactic and semantic complexity of the items. The recommended starting point for an average adult requires the person to silently read a sentence or short paragraph and verbally supply the missing word that appropriately completes the sentence. This subtest yields raw scores and standard scores.

Phoneme Detection Test

Although rhyming tasks are often used as an indicator of phonological awareness, more direct measures of phonological awareness have been difficult to obtain in deaf populations in large part due to insensitive test administration protocols. Many current measures (e.g., Rosner Test of Auditory Analysis Skills, the Lindamood Auditory Conceptualization Test, or the Comprehensive Test of Phonological Processing) require stimulus items or the subject's responses to be spoken or verbalized, which can be problematic for deaf subjects who do not speech read or use speech to communicate. Here we introduce a computer-based phonological awareness measure, the Phoneme Detection Test (PDT), which addresses these administrative confounds. This test was developed to measure phonemic awareness via detection of the presence of a single phoneme in individual, visually presented words (computer generation of these stimuli was achieved with Presentation version 0.81; www.neurobs.com). The test includes 150 high-frequency words with multiple or opaque orthography-to-phonology correspondences (e.g., "c" maps to /s/ and /k/ phonemes such as "cent" and "call"), divided into five target-phoneme sets of 30 items each: /s/, /g/, /j/, and /k/ (/k/ repeated for "ch" and "c" sets). Half the items contained target phonemes appearing in initial, medial, or word-final positions and the other half served as orthographic foils in which an alternate grapheme-to-phoneme correspondence was used. Subjects were instructed to respond as quickly and accurately as possible with keyboard buttons indicating "Yes" or "No" if an item contained the target phoneme. Nonverbal stimuli and response modality remove undesirable confounds from subjects' different communication modes and allow between-group comparisons of accuracy and reaction time. Explicit instructions and examples were given at the beginning of the test to ensure that subjects understood that the task was not to detect orthographic units, but phonemic units. In addition, each set was preceded by a four-item practice session. The order of set presentation was counterbalanced across subjects.

Spatial Memory Span

The Spatial Span (SS) subtest from the Wechsler Memory Scale-III measures the ability to hold a visual-spatial sequence of events in working memory (Wechsler, 1997). A three-dimensional board of nine cubes positioned on a base is used to administer visual-spatial sequences, ranging in difficulty from two to nine movements, with two trials at each level. Subjects are instructed to manually respond by touching the blocks in correct sequences, either forwards or backwards for Spatial Span

Forward and Spatial Span Backward. Total raw score (from Forward and Backward trials) is converted to an age-referenced scaled score. This test was included to provide a spatial analogue to the verbal memory span.

Verbal Digit Span

The Wechsler Adult Intelligence Scale-III (WAIS-III) Digit Span subtest requires repetition of numbers in sequences of increasing length, from 2 to 9 numbers with two trials at each difficulty level (Wechsler, 1999). The subject is given two strings of each length, the length increasing with each pair. If the subject repeats both sequences correctly he or she receives a score of 2, if only one is correct a score of 1, and if neither is correct no points are earned. Hence it is these scores that are reflected in the raw score (not the longest correctly repeated sequence). The score from forward and backward lists were combined and converted to an age-reference scaled score. As is typical for this test, an experimenter administered the DST in English for hearing and deaf oral subjects. Prior to taking the test, deaf oral subjects were given opportunities to be familiarized with the experimenter's mouth movements. Deaf signers and deaf cuers viewed a prerecorded Quicktime video in which the experimenter presented the digits in their respective languages, ASL, and English (via cued speech). Subjects were given opportunity to respond in their preferred mode or language.

Visual Version of the Digit Span

Because of difficulties in interpreting between-group differences for the traditional version of the Digit Span described above and the existence of sensory and language differences during task presentation (Boutla *et al.*, 2004; Wilson & Emmorey, 1998; Wilson & Emmorey, 2006a, 2006b), we also administered a visual version of the Digit Span Test to our subjects. Written task instructions and practice sessions were presented on a computer screen at the beginning of the test to ensure subjects understood the task. Digits were presented centrally on the screen in large black font and at the same pace as the traditional verbal version of the Digit Span (Presentation version 0.81, www.neurobs.com). Immediately after the presentation of number strings, a red square flashed briefly on the screen to signal the end of the trial and begin recall. To visually simulate the falling intonation used when the last digit in a string is uttered in the Verbal Digit Span, the last digit in a string was presented using a different colored font (red),to prompt the subject that the sequence is about to end. Subjects responded using the number keypad and were given opportunity to delete their response if they made keyboard errors.

Data Analysis

We compared the five groups (deaf users of ASL, oral English, and cued English as well as hearing nonsigners and hearing native signers) on each behavioral measure using one-way ANOVAs with significance defined as alpha <0.05. Where main effect of group was observed, pairwise multiple comparisons were made among each of the five groups. To estimate inter-measure reliability, the traditional Verbal Digit Span and the experimental visual version of the Verbal Digit Span were entered into a correlation analysis (with forward and backward raw scores combined). In addition, to establish the relationship between measures of reading with measures of STM and PA, measures from the PDT and the Digit Span (both the traditional verbal version as well as for the experimental visual version) were entered into nonparametric correlation analyses with Passage Comprehension and Word Identification Fluency scores.

Results

Neuropsychological and Behavioral Tests

Table 1 shows the groups' demographics as well as their behavioral scores. As described

TABLE 1. Demographic, Neuropsychological, and Behavioral Measures Expressed as Mean Score (*SD*)

	Hearing	Hearing ASL	Deaf ASL	Deaf CS	Deaf Oral	Significance
N	8	9	13	9	8	
Demographics						
Age (years)	22.6 (3.1)	30.4 (5.8)	23.1 (3.6)	29.4 (3.6)	25.0 (3.5)	.000
Gender	4F	9F	7F	4F	2F	
Neuropsychological and Behavioral Scores						
Performance IQ	117.75 (6.7)	114.89 (10.5)	109.92 (10.0)	112.88 (8.8)	112.50 (8.7)	n.s.
Reading (accuracy)						
TSWRF (word identification)	115.62 (13.6)	108.56 (14.0)	105.15 (16.9)	122.55 (8.4)	113.87 (12.1)	n.s.
WJ-III Comprehension	119.5 (11.2)	112.67 (13.1)	100.15 (11.9)	106.0 (4.6)	102.5 (7.9)	.001
Short-term memory						
Spatial Span (SS)	109.37 (9.8)	106.67 (8.3)	108.85 (11.4)	97.77 (14.2)	101.87 (6.5)	n.s.
Digit Span Verbal (SS)	121.88 (16.2)	108.89 (14.5)	96.92 (13.9)	105.00 (10.3)	97.37 (10.0)	.002
Digit Span Verbal (raw)	23.75 (4.7)	19.78 (3.8)	16.46 (4.0)	18.22 (2.7)	16.75 (2.9)	.001
Visual version of Digit Span (raw)	22.33 (2.4)	21.44 (3.9)	15.81 (3.7)	15.87 (3.0)	11.86 (2.3)	.000
Phonemic awareness						
PDT accuracy (%)	93.7 (7.3)	93.4 (5.2)	65.2 (14.5)	86.4 (12.3)	87.6 (6.9)	0.000
PDT RT (ms)	1156 (335)	1854 (665)	2848 (1027)	1819 (777)	2577 (1332)	0.002

above, subjects were selected in such a way that they were matched for Performance IQ, $F(4, 42) = .985$, $P < 0.426$, and reading fluency as measured by TSWRF, $F(4, 42) = 2.461$, $P = 0.060$. However, despite their generally equivalent performance on word-recognition fluency, we found a main effect of group in the Passage Comprehension subtest, $F(4, 42) = 5.313$, $P < 0.001$. Post-hoc comparisons revealed that performance of the hearing nonsigning group was significantly higher on reading comprehension than the deaf signing (Tukey's HSD $= 19.34$, $P < 0.002$) and oral (Tukey's HSD $= 17.00$, $P < 0.018$) groups, but not the hearing signers or deaf cuers ($P > 0.05$). Hearing signers were not significantly different from any of the three deaf groups ($P > 0.05$), nor were there significant differences when comparing any of the three deaf groups with each other. Therefore the hearing nonsigning group was the only group at odds compared to the others with a significant advantage for reading comprehension.

Phoneme Detection Test

Computer difficulties resulted in data loss from six subjects for this test (H = 2, DC = 1, DO = 1, and DA = 2). Main effect of group was observed in the remaining PDT data on measures of performance accuracy, $F(4,36) = 12.26$, $P < 0.001$, and reaction time $F(4,36) = 4.33$, $P = 0.006$. Post-hoc comparisons revealed that the deaf signing group was significantly less accurate (Tamhane's T2, $P < 0.05$) on phoneme detection compared to the other four groups. However, deaf signers reported no significant difference in reaction times when compared to the other groups ($P > 0.05$) except for the hearing nonsigners, who were faster than the deaf signers (Tamhane's T2, $P = 0.002$). Accuracy and reaction times for the deaf cueing group was comparable to that of the hearing control group, hearing signers, and deaf oral users (Tamhane's T2, $P > 0.05$). The deaf oral group also demonstrated statistically indistinguishable accuracy and reaction times when compared to the hearing nonsigning group and hearing signing group (Tamhane's T2, $P > 0.05$).

Spatial Memory Span

WMS–Spatial Span revealed no significant group differences among the five groups, $F(4, 42) = 2.054$, $P = 0.104$.

Verbal Digit Span

The traditional verbal version of Digit Span test from the WAIS-III revealed significant group differences in raw scores, $F(4, 42) = 5.67$, $P < 0.001$. Post-hoc comparisons between the three deaf and two hearing groups showed that the hearing nonsigners performed significantly better (Tukey's HSD, $P < 0.05$) than all other groups except hearing signers (Tukey's HSD = 3.97, $P = 0.198$). The hearing ASL signers did not differ significantly from any of the deaf groups and no significant differences were found among the three deaf groups (Tukey's HSD, $P > 0.05$).

Visual Version of the Digit Span

Computer difficulties resulted in some data loss for the Visual Digit Span (H = 2, DA = 2, DC = 1, DO = 1). For the remaining data, significant between-group differences were observed in raw scores, $F(4, 36) = 12.63$, $P < 0.001$. Post-hoc comparisons indicated that all three deaf groups performed significantly lower than the two hearing groups in all pairwise contrasts (Tukey's HSD, $P < 0.01$). However, all deaf groups showed no significant differences with each other (Tukey's HSD, $P > 0.05$). Hearing nonsigners were not significantly different from hearing signers (Tukey's HSD = .889, $P = 0.986$).

Correlation Analyses

To assess the relationship between the standard verbal versions of the Digit Span and our experimental visual version of this test, we entered the data into a nonparametric correlation analyses and found that the two measures were significantly correlated to each other ($\tau = .602$, $P < 0.001$).

To estimate the relationship between phonemic awareness skills (as measured by the PDT) and reading ability, nonparametric correlation analysis (Kendall's tau) was performed between PDT accuracy scores and performance on the TSWRF as well as Passage Comprehension scores. Surprisingly, the first revealed no significant correlation between PDT accuracy and TSWRF. The second showed a positive correlation ($\tau = .305$, $P < 0.006$; two-tailed) between PA skills and reading comprehension. Reaction time from the PDT was negatively correlated to the above same measures (TSWRF: $\tau = -.291$, $P < 0.01$; two-tailed and Passage Comprehension: $\tau = -.248$; $P < 0.05$, two-tailed).

To estimate the relationship between STM memory and reading measures, both the traditional Verbal Digit Span and the experimental visually presented version of the Verbal Digit Span were entered into nonparametric correlation analyses and found to be significantly correlated with the Passage Comprehension (DS-Verbal: $\tau = .323$; DS-visual version of the verbal: $\tau = .409$, $P < 0.002$; two-tailed). However, neither version of the Digit Span was correlated to word identification fluency as measured by TSWRF (DS-Verbal: $\tau = .114$; DS-Visual: $\tau = .082$, $P > 0.05$).

Discussion

With a few exceptions (i.e., Charlier & Leybaert, 2000; LaSasso *et al.*, 2003), previous empirical studies examining the impact of deafness on skills that support reading have focused on deaf signers, making it difficult to dissociate the effect of deafness from early language experience. Inclusion of deaf individuals who acquired English natively via visual means (oral communication or cued speech) along with deaf users of ASL will help us disentangle the effect of deafness and language experience on phonological awareness and verbal short-term memory, two of the three core predictors of reading achievement (Wagner & Torgeson, 1987). The first aim of the present study was to explore the PA skills of deaf cuers (who have full, unambiguous access to the phonological structure of traditionally spoken languages) relative to other deaf and hearing groups. Then, by examining verbal working memory of deaf nonsigners as well as the more traditionally studied group of deaf signers, the second aim was to gain further insight into the role visual language plays in the capacity to retain lexical items in short-term memory.

Phonemic Awareness

Because commercially available measures of phonological awareness are not suitable for deaf populations (see Tractenberg, 2002), the PDT was developed to probe phonological coding skills in deaf participants using visual stimuli and nonverbal responses. As expected, deaf native signers of ASL did not perform well on phonemic detection of English words, reflecting their lack of experience with spoken English phonology. Specifically, the deaf signing group was significantly less accurate on the PDT than all other groups. Mean reaction time for the deaf signers was longer on the PDT, but this difference was significant only in comparison to the hearing nonsigning group. Only two deaf signers showed greater than 85% accuracy on the PDT, and deaf signers in general performed at or slightly above chance during the detection of phonemic units, despite being good readers.

On the other hand, deaf cuers and deaf oral users had accuracy scores that were statistically indistinguishable from those of either hearing groups. With an average accuracy above 85% on the PDT, both of the English-native deaf groups (cuers and oral users) clearly demonstrated robust awareness of the phonological structure of English lexical items, even when certain phonemes were not explicitly revealed in the orthography. To our surprise, deaf cuers and oral users were not different from each other during this phonological coding task (based on accuracy and reaction times). More direct access to the phonemic stream of English in deaf cuers would have predicted an advantage for this group over the oral group (cuers had shorter but not statistically different reaction times), but such a benefit was not observed on this test.

Correlation analyses revealed that although accuracy on the PDT was not correlated to performance on word identification fluency (measured by the TSWRF), it was correlated with Passage Comprehension; and reaction time on the PDT was correlated with both the TSWRF as well as reading comprehension, suggesting that a relationship does exist between reading and PA skills in the context of the speed by which subjects perform the PDT task. The absence of a correlation between accuracy in word-recognition fluency and PA is somewhat surprising, as studies of hearing populations frequently report that measures of phonemic coding skills correlate with word-reading accuracy. The reason for a lack of a correlation between the PA test and the TSWRF is most likely due to the fact that the TSWRF task relies more on sight word recognition than addressed phonology. Addressed phonology is probed more directly during tests of reading aloud, especially the reading of pseudowords.

In sum, PA skills are not well developed in deaf users of sign language, even though they have acquired proficient reading skills. This suggests that under some circumstances proficient reading can be attained in the absence of PA skills. Future studies will need to determine whether there are other skills, linguistic or otherwise, that are more strongly developed in deaf signers with good reading ability and how these facilitate their reading. We also found that deaf cuers performed more like hearing subjects and significantly better than deaf signers on the PA test. Their ability to detect phonemic units suggests they have been facilitated by lifelong use of manual cues to visually access English phonology. However, since our oral subjects performed equally well as the cuers, it seems that access to the phonological representation of English can also be obtained without the use of cues.

Short-Term Memory

There has been an ongoing debate as to whether retention spans in short-term verbal memory are lower in people who are deaf. Some have argued that studies in which differences have been observed in deaf population may be confounded by the delivery of the tests, that is, administration in sign language compared to English may introduce other variables that lead to shorter retention spans. Here we addressed this question using a two-pronged approach. First, the inclusion of deaf participants who use English to perform the task (instead of ASL) allows for a more comparable assessment between hearing and deaf groups. Second, we devised a visual version of the traditional Verbal Digit Span as a way to equalize the stimuli presentation and response mode between hearing and deaf groups. Together this allowed us to examine whether verbal STM is affected by sensory experience, language experience or modality of test presentation.

Our overall finding was that although all five groups were comparable on the Spatial Span tests, there were profound group differences on performance of the Verbal Digit Span. All three deaf groups showed shorter digit retention when compared to the nonsigning hearing group during the traditional version of the Digit Span and, further, all three deaf groups showed shorter digit retention when compared to both hearing groups in an experimental visual version of the Digit Span where subjects responded to visual stimuli using a keyboard.

Our first observation of lower performance on the Digit Span is consistent with recent findings (Boutla *et al*., 2004; Bavalier *et al*., 2006), that deaf signers exhibit shorter digit span for numbers presented in ASL compared to hearing nonsigners. When examining the longest correct digit length attained, our hearing subjects achieved spans of 7.2 (nonsigners) and 6.3 (signers) and our deaf subjects had spans of 4.9 (signers), 5.4 (cuers), and 5.0 (oral). These findings are largely consistent with the digit spans described by Bavalier *et al*. (2006) for signers. In addition to this observation, Boutla and colleagues also reported decreased serial item recall in hearing signers when they viewed the stimuli in ASL compared to when they heard the stimuli in English. Together these results suggest a detrimental effect of ASL on measures of verbal retention, but, perhaps somewhat surprisingly, our deaf cueing and oral groups also exhibited significantly lower digit spans than the hearing nonsigners. Since both the cueing and oral groups received the stimuli in their native English language and linguistic modality (cued or orally), the discrepancy in short-term recall of digits described in the literature cannot be solely attributed to signed languages. Our second test of verbal short-term verbal memory was given in the visual modality to all participants and resulted in all three deaf groups performing similarly to one another and significantly lower than the two hearing groups. Together these results suggest that even when language experience or modality of test presentation are taken into consideration, there are differences among hearing and deaf subjects in their ability to retain digits.

These findings suggest that the use of the visual-spatial modality (rather than the auditory modality used by hearing subjects) to receive and hold linguistic items in working memory presents a greater processing load, and results in lower item recall. This conclusion is consistent with the view put forward by Bavelier and colleagues, suggesting that visual modality is a limiting factor in working memory (Boutla *et al*., 2004; Bavalier *et al*., 2006). In this context it is also worth considering that deaf subjects did not only differ from the hearing subjects in their retention span and that all deaf groups performed similarly to one another, but also that the deaf signers did not show any improvements in performance on the experimental visual version of the digit span compared to the traditional verbal version. Specifically, our efforts to remove any linguistic or modality bias in stimuli presentation and recall responses had little positive effect on the performance of our deaf participants. This is consistent with findings where visually presented non-nameable items have reduced hearing subjects' capacity for serial item recall (Alvarez & Cavanagh, 2004; Cowan, 2001).

Finally, it is of interest to examine working memory spans in the context of our other measures. Deaf cuers performed similarly to the hearing subjects on word identification fluency, and phonemic awareness, but they had significantly lower digit-span performance. This suggests that good reading skill can be attained in the absence of strong working memory skills, and again suggests that skills traditionally thought of as predicting reading outcome in hearing subjects (Wagner & Torgeson, 1987) may not be suitable in gauging reading achievement in deaf students.

In sum, we found that deaf subjects regardless of communication or language background, had lower digit-span retention than hearing subjects, while spatial span was comparable amongst all groups. Further, we found no differences in performance among all three deaf groups even though their language background might have predicted differential ability on memory span. The findings suggest that longer digit recall in hearing compared to deaf subjects can be explained by the availability of the articulatory loop that is utilized for the sequential nature of the auditory channel in working memory.

Conclusion

The goal of the present study was to gain some insight into the cognitive and linguistic abilities of deaf people who are skilled readers yet have been raised with a variety of communication systems, namely ASL, cued speech, or the oral-aural method. We found deaf native signers of ASL did not do well on detection of hidden English phonology in visually presented words, while deaf cuers and deaf oral users had phonological performance comparable to those of hearing subjects. Second, we examined the digit span of deaf and hearing subjects and found that all three deaf groups performed similarly to one another and weaker than hearing subjects. Since deaf cuers and oral users receive the digit stimuli in the same language as hearing groups via a different visual medium, we conclude that the use of sign language does not have a detrimental effect on serial recall of linguistic items. Instead, it appears that linguistic information processing in the visual channel creates additional processing burden on short-term memory capacity and subsequent recall. This was confirmed by a second measure of the Digit Span that did not involve the use of manual languages in its administration. Taken together, the findings support the idea put forward by Bavalier *et al*. (2006) that the articulatory loop in working memory is most advantageous when speech articulation is used to encode linguistic items and that the visual nature of linguistic stimuli triggers a decrease in STM span. Finally, our results demonstrate that among deaf subjects skilled reading can be attained despite lower working memory abilities and, in the case of signers, despite lower STM and phonemic awareness skills. This strongly suggests that deaf subjects' reading skills are facilitated by abilities other than those traditionally considered to be important in hearing students.

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Conflicts of Interest

The authors declare no conflicts of interest.

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